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# Scalable Mode Division Multiplexing using Orbital Angular Momentum Mode Groups in Ring Core Fibres

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**Abstract:** Our calculations and experiments demonstrate that modular 4x4 MIMO schemes based on OAM mode groups in ring core fibres provides optimum scalability amongst fiber-based spatial or mode division multiplexing schemes.

**OCIS codes:** (060.4230) Multiplexing, (050.4865) Optical vortices; (060.2330) Fiber optics communications;

## 1. Introduction

As the single mode fibre (SMF) capacity approaches the nonlinear Shannon limit, techniques using space division multiplexing (SDM) or mode division multiplexing (MDM) in multi-mode fibres have been increasingly investigated in order to provide new degrees of freedom to achieve higher capacity [1].

SDM launches optical signals channels into spatially diverse apertures at the input facet of the fibre and detects the signal at corresponding apertures at the fibre output facet. SDM can be implemented using multi-core fibres (MCF) [2]. When cores are closely packed, the extreme case is a merged fibre core, i.e., a multi-mode fibre (MMF). In general, each SDM channel will excite all modes supported by the MMF, while MDM selectively launches optical signals channels into individual (or groups of) modes [3] and de-multiplex and detect each mode (group) at the output facet. While multi-input multi-output (MIMO) signal processing has been a necessity in SDM schemes, MDM schemes can exploit the orthogonality of modes to either reduce or completely remove the need for MIMO, assuming modes don't couple strongly during the propagation, or their coupling matrix is known [4]. One example is the use of orbital angular momentum (OAM) modes by designing ring core fibres (RCF) that break their degeneracy [5].

Arguments have persisted on the spectral efficiency or capacity that can be supported by multi-mode fiber based spatial or mode division multiplexing schemes, and their relative potentials of scalability. We report a rigorous comparison of the spectral efficiency (SE), signal processing complexity (SPC) between SDM and MDM communications schemes using typical multi-mode fibre structures including step-index fibres (SIF), graded index fibres (GI-MMF) and RCF. We predict that the RCF-based MDM scheme is more scalable than the other schemes as it only requires modular 4x4 MIMO processing, and on the other hand does not require difficult fiber designs for OAM-based MIMO free transmission. We experimentally demonstrate this scheme, achieving substantial capacity-length product values, and we discuss its further up-scaling.

## 2. Theoretical Scalability

In practical MMFs, mode coupling gives rise to signal channel crosstalk noise therefore reduces channel capacity according to Shannon's Theorem. Signal channels in SDM are spatial apertures whereas in MDM are the modes themselves. Signal processing may be used to suppress crosstalk noise and recover the information transmitted [6], at a cost of additional hardware, software and energy consumption. A MIMO system over MMF with N transmitters, N receivers and additive noise, and applying a 'water-filling' algorithm that allocates signal power optimally amongst channels to achieve higher overall SE, has spectral efficiency (SE) as [8, 9]:

$$SE = \sum_{i=1}^N \log_2 \left[ 1 + \frac{1}{\sigma^2} (\lambda_i \mu - \sigma^2)^+ \right] \text{ (b/s/Hz)} \quad (1)$$

where  $\sqrt{\lambda_i}$  is the singular value of normalized channel matrix  $H$ .  $a^+$  denotes  $\max(a, 0)$ ,  $\sigma^2$  is the receiver noise variance and  $\mu$  is the required water-filling power level.

The SPC of FIR filter based adaptive frequency-domain equalization FDE can be measured by the number of complex multiplications per channel per second, given by [7]

$$SPC = \frac{(4+2N) \cdot C_{rad} \cdot N_{FFT} \cdot \log_2(N_{FFT}) + 2N \cdot N_{FFT}}{(N_{FFT} \cdot N_{MD} + 1)} R_s \quad (2)$$

where  $C_{rad}=0.5$  for a radix-2 FFT and  $N_{FFT} = 2^{\lceil \log_2(2*N_{MD}) \rceil}$  the FFT block length. In order to realized adaptive filter update, overlap-save FFT can be used to avoid cyclic prefix which may decrease net throughput. We assume radix-2 FFT and 50% overlap-save.  $N_{MD}$  is the number of sampling points that has to be stored due to the group velocity dispersion between modes that dictates the number of filter taps for each equalization block, which is also a contributing factor to hardware cost.

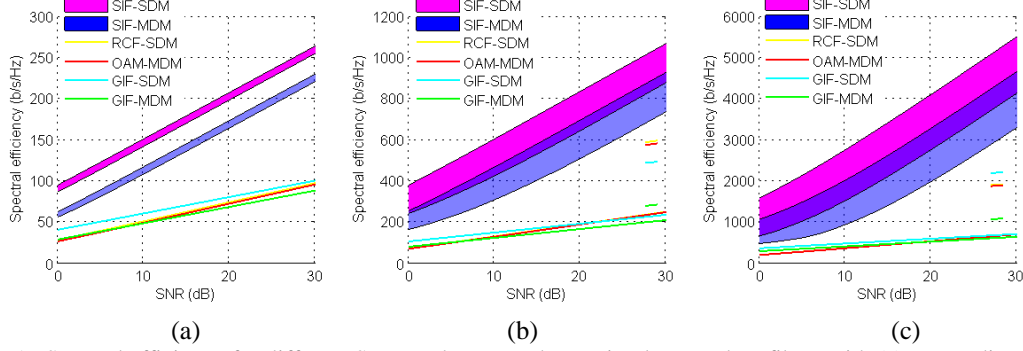


Figure 1. Spectral efficiency for different SDM and MDM schemes implemented on fibres with (a) core radius = 10  $\mu\text{m}$ , (b) 20  $\mu\text{m}$ , and (c) 50  $\mu\text{m}$ . The spread in the case of SIF represents SE values from weak to strong coupling regime.

As shown in Figure 1, at moderate to high SNR, SIF can theoretically support 5-10 times higher spectral efficiency over other schemes because it has the largest number of channels (also see Figure 2(c)). The difference between the SDM and MDM is because of the 4x more channels supported by SDM. For GIF based MDM, RCF based SDM, and RCF based OAM-MDM schemes, the calculated SE values are quite similar to each other. At fibre radius of 20  $\mu\text{m}$  which is close to commercially available MMFs (such as OM4 fibre), they all support spectral efficiency of  $>100$  b/s/Hz for moderate SNR, which is significantly higher than the nonlinear Shannon limit of  $\sim 10$  b/s/Hz in standard SMF.

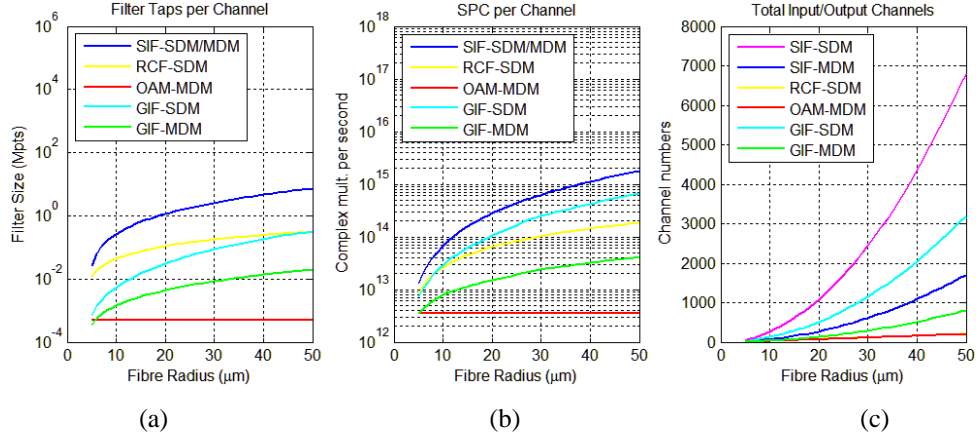


Figure 2. (a) Total memory size requirement, (b) Multiplications per second for FDE, and (c) Total Channel Numbers

The signal processing complexity (SPC) and hardware requirements to exploit above SE are shown in Figure 2, assuming the use 32 GBaud 16 QAM, and the SDM and MDM schemes are populated by such channels until the spectral efficiency as plotted in Figure 1 is fully utilized.

According to Figure 2 (a), SIF based schemes require large tap numbers because of the large GVD between all the modes. For GIF and RCF, mode-group based processing reduces the tap number due to the near-degeneracy within mode groups, with OAM-MDM on RCF need the least. According to Figure 2(b), SIF requires two orders of magnitude higher SPC over the RCF MDM while the number of effective channels supported is only different by a factor of  $\sim 6$  (Figure 2(c)).

These results point to the prediction that RCF-based MDM scheme will be more scalable due to its reasonable capacity or SE that is achievable with the lowest SPC and DSP cost.

#### 4. Experiments

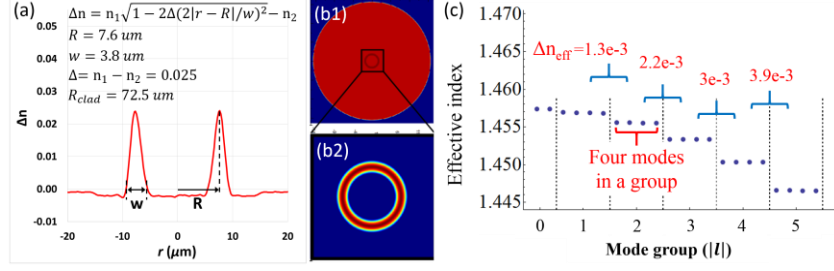


Figure 3. (a) Measured index profile of a GIRCF and its design parameters. (b1-b2) Cross-sectional index diagram of the GIRCF. (c) Effective indices of all supported OAM modes and the inter-group effective index difference between them.

We designed a raged index ring core fibre (GI-RCF) with a parabolic index profile over the ring-core width (Figure 3), supporting mode-groups up to  $|l|=5$ , each group containing four OAM modes  $\langle \pm l, \pm s \rangle$ , where  $\pm s$  refers to left- or right-handed circular polarizations. The fiber designed to have  $\Delta n_{\text{eff}} > 10^{-3}$  between mode groups of  $|l|=1$  and 2 and linearly increasing with  $|l|$ , while the intra-group  $\Delta n_{\text{eff}}$  is  $\sim 10^{-5}$ . The measured attenuation is  $\sim 1$  dB/km for all modes and the inter-mode group coupling between  $|l|=4$  and 5 is  $-15$  dB over 10 km.

Using 5 - 10 km of this fibre, we have demonstrated MDM-WDM coherent transmission schemes over 8 OAM modes (belonging to two mode groups  $|l|=4$  and 5) and up to 12 wavelengths [10]. For each wavelength, only modular 4x4 MIMO is used for intra-group equalization while inter-group coupling is suppressed by the fibre design. After transmission, each group of modes with the same  $|l|$  value is demodulated into two polarization multiplexed channels simultaneously and the 8 output waveforms (I/Q for each mode) from the coherent Rx are recorded by two synchronized real-time oscilloscopes and processed off-line by a 4x4 MIMO equalizer whose coefficients are updated using the constant modulus algorithm (CMA) with only 15 taps. We have achieved transmission of all channels exceeding the FEC threshold BER, with both QPSK and 16QAM modulation formats, with maximum capacity of 6.4 Tbit/s, SE of 12.8 bit/s/Hz, and maximum capacity-length product of 64 Tbit/s · km. The transmission distance and capacity can be further increased by reducing the fibre attenuation.

## 5. Conclusions

OAM-MDM schemes based RCFs have been shown to provide the optimum trade-off between capacity, MIMO complexity and practicality by (1) enabling modular MIMO that reduces SPC to practical levels, (2) full use of fibre mode space, (3) easy fibre design and fabrication, and (4) easier mode DEMUX.

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